

Nuclear Suppression of Hadroproduction

S.V.Akulichev

Institute for Nuclear Research,

60-th October Anniversary Prospect 7a, Moscow 117312, Russia.

February 9, 2008

Abstract

We demonstrate that the main part of the observed nuclear suppression of dilepton and charmonium production, especially the x -dependence of the suppression, can be explained by the absorption of fast initial partons. We assume the absorption to be x_1 -dependent and determine the empirical form of this dependence. Several reactions at different energies are described with the same parametrization of the absorption cross section. The factorization theorem constraints and some alternative models are discussed. The obtained description of data allows to make conclusions about the origin of nuclear effects in hadro- and electroproduction. In particular, it is concluded that the parton recombination and the excess pion contribution are unimportant in nuclei and an indication of excess gluons at $x_2 \sim 0.1$ is observed.

PACS numbers: 24.85.+p, 25.75.+r, 12.38.Aw, 13.85.Ni

I. INTRODUCTION

Several effects have been considered in order to explain the observed strong suppression of J/ψ -production in hadron-nucleus collisions[1, 2]. We can mention some of them: the intrinsic charm[3], the comover interaction[4], the recombination of nuclear partons [5, 6], the interaction of non-singlet final parton configurations[7, 6], the elastic rescattering of initial partons[8], the energy loss of initial partons[9] and the absorption of initial partons[10]. However, we agree with the authors of Ref.[11] that the x -dependence of charmonium production suppression has not yet been described. Without a reliable description of the charm production suppression in hadron-nucleus interactions, it is hard to analyze this effect in heavy ion collisions while searching for the quark-gluon plasma signals[12]. Moreover, a nuclear suppression has been observed in the Drell-Yan (DY) production by pions[13] and, though much less, by protons[14]. A self-consistent description of hadroproduction suppression in nuclei, as well as of the nuclear effects in electroproduction[15], is now one of the important goals of high energy nuclear physics. We here develop a model, which successfully describes several reactions at different energies and, as we try to argue, does not contradict the true factorization forecasts.

We now briefly overview the status of the above mentioned models. 1) The intrinsic charm model is, in principle, able to account for the observed x_F -dependence of the J/ψ -suppression, namely the suppression increasing with x_F . However, the experimental searches for the intrinsic charm in protons[16] have not revealed any charm signals. With the experimental upper limit on the amount of the intrinsic charm in protons[16], this mechanism cannot explain the observed charm production suppression. Moreover, this mechanism is irrelevant for the DY production by pion, where the suppression is also significant, as it will be shown below. 2) The comover interaction is most effective at negative x_F , because the density of comovers increases for less energetic produced quarkonia. In fact, a strong suppression was observed in quarkonium production at negative x_F [17]. In the present article we are concerned with the region of positive medium and large x_F of produced charmonia, where the comover interaction must be minor. 3) In agreement with the strong factorization, the parton recombination models suggest that the initial state effects in hadroproduction are in-

cluded in nuclear structure functions. It has been assumed[5] that nuclear structure functions are suppressed at small x_2 due to QCD recombination of partons from neighbour nucleons. This mechanism has been widely used to explain the nuclear shadowing in electroproduction at low x_2 . This effect would lead to an x_2 -scaled nuclear suppression of quarkonium and dilepton hadroproduction. However, a comparative analysis of the data at different proton energies clearly shows[2, 11] that the J/ψ -suppression is scaled on x_F or x_1 , but not on x_2 . It seems that these data create serious troubles for the nuclear parton recombination hypothesis, as we will argue below. 4) Final state interactions of produced non-singlet parton configurations can be responsible for a suppression of quarkonium production, because these interactions are not restricted by the color transparency. However, there is no physical reason why this effect should increase with x_F at large x_F . Moreover, this effect cannot explain the DY production suppression. Therefore the final state interactions of produced heavy quarks cannot be the only mechanism of nuclear suppression. 5) The elastic rescattering of initial partons naturally explains the dilepton and quarkonium yield increasing with p_T . However this mechanism alone, if not completed by the energy loss of partons, makes no predictions for the x -dependence of hadroproduction suppression. 6) The two remaining models, assuming the energy loss (EL) of fast initial partons due to soft elastic rescattering[9] and the absorption of those partons[10], will be considered below in more detail. We first discuss these two models with respect to the factorization theorem.

The cross section factorization in large- Q^2 reactions can be represented, in the case of DY production, in the following form[18, 19]

$$d\sigma^{DY} \sim \int_0^1 \frac{dx_1}{x_1} \frac{dx_2}{x_2} f_1^{DY}(x_1) H(x_1, x_2, Q^2) f_2^{DY}(x_2), \quad (1)$$

where $f^{DY}(x)$ are parton densities containing all non-perturbative long-distance effects and H , being a projectile- and target-independent function, describes the hard parton-parton subprocess. The integration over transverse momenta and the Q^2 -evolution of structure functions are implied in Eq.(1). In the lab. frame, the subscripts 1 or 2 correspond to projectile or target, respectively. In a general case, when the functions $f(x)$ depend on the reaction under consideration, the form (1) corresponds to the weak factorization. The strong

factorization means that the structure functions are reaction-independent, e.g. the structure functions measured in electroproduction are equal to $f^{DY}(x)$ (integrated over transverse momenta). The limitations of the factorization have been discussed in several papers (see, e.g., Refs.[19]-[22]). In particular, it was obtained[21, 19] that in the case of collinear active-spectator parton interactions, followed by the productive annihilation of the active parton, the strong factorization is valid if

$$Q^2 \gg x_2 L M l_T^2, \quad (2)$$

where L and M are the target length (in the rest frame) and mass and l_T is the transverse momentum, transferred in the active-spectator interaction. From Eq.(2), it is reasonable to expect that the corrections to factorization, in the case of collinear active-spectator rescattering, should vanish as $1/Q^2$. It was also concluded[22] that the maximum energy loss of an incident parton due to induced gluon radiation, which is expected to be the main source of energy losses, is

$$\Delta_{max} x_1 = k_T^2 L / 2 E_{lab}, \quad (3)$$

where k_T is the transverse momentum of the radiated gluon and E_{lab} is the projectile energy. This corresponds to an average parton energy loss per unit length $dE/dz \sim 0.3 GeV/fm$ [22]. The limitations (2) and (3) directly concern the EL-model, because this model assumes the initial state interactions of the type studied in Refs.[21, 19, 22]. This means that in the parametrization for the average parton energy loss in nuclei[9],

$$\Delta x_1 = \kappa x_1 C_i (Q_0/Q)^n A^{1/3} \quad (4)$$

($C_g = 3$ for gluons, $C_q = 4/3$ for partons and $Q_0 \approx 4 GeV$), it is more reasonable to use $n=2$. This choice is also supported by the observation that the leading contribution to the DY production is twist 4. The limitation (3) was significantly violated with $\kappa \approx 0.003$, used in Ref.[9] to fit the data for the charmonium suppression. Nevertheless we will present below some numerical results of the EL-model, considering this model as a possible alternative for our model.

The absorption of fast initial partons by nuclear nucleons corresponds to all parton-parton processes, which remove the active parton from the production channel. These processes are

not followed by the productive annihilation of the active parton, in contrast to initial state interactions assumed in the EL-model. An example of such processes is a particle production on front nucleons: though the formation of produced particles takes a long time, the momentum transfer in productive parton-parton collisions can be quite large, of the order of the projectile momentum P . The last statement follows from the observation that at high energies many of produced particles are concentrated around the central rapidity [23]. New particles with central rapidity cannot be produced as a result of only soft parton-parton collisions. After a large momentum loss, an active parton can hardly participate in the production on backward target nucleons. In the terminology of Ref.[19], the absorption of active partons can be described by hard active-spectator interactions or collinear active-spectator interactions with large momentum transfer $l_+ \sim P$. We emphasize that the proofs of the strong factorization performed in Refs.[18]-[21] do not concern these two types of active-spectator interactions and the target-length condition (2) was not proved for these initial state interactions. For example, the strong factorization has not been proved when $l_+ \sim P/ML$ (see Eq.(2.24) from Ref.[19]). The cancellation of two-step diagrams, demonstrated in Ref.[20], is not effective for these interactions because the coherency of parton-parton interactions in nuclei is lost when l_+ is much larger than the inverse internucleon distance[21, 10]. Furthermore, the limitation (3), obtained for the induced gluon radiation, was not proved for some other initial state interactions, for example for the elastic active-spectator scattering with large l_+ . However, it is reasonable to expect that the contribution of large momentum transfer collisions is small compared to total hadron-hadron cross sections. This limitation will be fulfilled in our model: the parton-nucleon absorption we introduce manifests itself in an average proton-proton cross section $\sigma_{abs}^{pp} \leq 1mb$. The large effect of the parton absorption in nuclear hadroproduction reactions is explained by the assumed x_1 -dependence of the absorption: it is concentrated at large x_1 . In some cases the hadroproduction is sensitive to large x_1 , but the contribution of the large- x_1 region to the total hadron-hadron cross section is small because structure functions vanish at large x . Note that the parton absorption we discuss has a negligible effect for one-nucleon targets and the strong factorization is fulfilled in this case, in agreement with well known experimental results. On the other side, the

violation of strong factorization in some hadron-nucleus reactions is an experimental fact, as it will be shown below. We will introduce a physically motivated parametrization to fit this violation in one reaction with a better statistics and more sensitive to the initial state absorption (J/ψ -production by 800 GeV protons) in order to study nuclear effects in all other reactions. In other words, we will assume that not the strong but the weak factorization is valid for nuclear targets.

II. THE MODEL

As we argued above, the initial state parton-nucleon absorption can take place due to hard and semi-hard parton-parton interactions. Therefore it is reasonable to assume that the inclusive parton-nucleon absorption cross section is a function of x_1 , i.e. $\sigma_{abs}^i \equiv \sigma_{abs}^i(x_1)$, where $i = g, q$ denotes gluons or quarks. The weak factorization of hadron-nucleus cross sections can now be reformulated as (see Eq.(1))

$$f_1^{DY}(x_1) = F^{DY}(x_1, A)f_1(x_1), \quad (5)$$

where $f_1(x_1)$ is the "intrinsic" projectile parton distribution and F is the factor describing the parton absorption effects. In quarkonium production, the factor F^Q can be also x_F -dependent due to final state interactions of produced partons. The final state interactions can account for possible comover interactions[4] and/or interactions of non-singlet configurations [7]. However, as we mentioned above, these final state interactions are expected to change slowly in the positive- x_F region we are concerned with. Therefore we will assume that an x -dependence of suppression factors F is accounted for by the x_1 -dependence of $\sigma_{abs}^i(x_1)$. The final state effects in quarkonium production will be represented by a constant cross section σ_f . In our earlier work[10], we have used constant cross sections σ_{abs}^i to describe initial state effects and the results of the present paper will significantly differ from the results of Ref.[10].

In the case of the square well form of nuclear density, the factor F^Q for the quarkonium production ($\sigma_f \neq 0$) is given by the eikonal form

$$F_i^Q(x_1) = \frac{3}{\sigma_f - \sigma_{abs}^i(x_i)} \left\{ \frac{\sigma_{abs}^{i3}(x_1)}{c_{abs}} [1 - e^{-c_{abs}^{i3}}(1 + c_{abs}^i)] - \frac{\sigma_f}{c_f^3} [1 - e^{-c_f}(1 + c_f)] \right\}, \quad (6)$$

where $c_{abs,f} \equiv 2\rho\sigma_{abs,f}R_A$ and the nuclear density and radius are denoted by ρ and R_A . For the DY production ($\sigma_f = 0$), this equation can be rewritten as

$$F_i^{DY}(x_1) = \frac{3}{c_{abs}^3} \left[\frac{c_{abs}^2}{2} + e^{-c_{abs}^i} (1 + c_{abs}^i) - 1 \right]. \quad (7)$$

In Eqs.(6) and (7) we assumed that the exclusive production cross section is much smaller than σ_{abs}^i or σ_f .

We have to determine the functions $\sigma_{abs}^i(x_1)$. The physical hadron-hadron absorption cross section is given by

$$\sigma_{abs}^{hh} = \sum_{i=g,u,d,\dots} \int dx_1 \sigma_{abs}^i(x_1) f^i(x_1). \quad (8)$$

Since parton distributions diverge as $x \rightarrow 0$, we must assume $\sigma_{abs}^i(x_1 = 0) = 0$ in order to obtain a finite σ_{abs}^{hh} . A phenomenological analysis of the J/ψ -suppression has shown that the data are better described when $d\sigma_{abs}^i(x_1 = 0)/dx_1 = 0$ as well. In this case we must assume that $d\sigma_{abs}^i(x_1 = 1)/dx_1 = 0$. This condition can be obtained from Eq.(8) using the probabilistic interpretation of parton distributions $f^i(x)$. Taking into account these limitations, we found that the functions

$$\sigma_{abs}^i(x_1) = \sigma_{max}^i \sin^6\left(x_1 \frac{\pi}{2}\right), \quad (9)$$

fit well the empirical x_F -dependence of the J/ψ -suppression in proton-nucleus collisions at 800 GeV. We will use the form (9) to describe all reactions. The function $\sin^6(x\frac{\pi}{2})$ is shown in Fig.1. The parameters σ_{max}^i characterize the strength of absorption and are extreme values of hadron-hadron absorption cross sections when the projectile hadron is composed of only one parton i (when $x_1 = 1$ for this parton). It is clear from Eq.(8) and Fig.1 that the physical value σ_{abs}^{hh} is much smaller than σ_{max}^i ($\sigma_{abs}^{hh}/\sigma_{max}^i \sim 2\%$). We may assume $\sigma_{max}^q = \frac{4}{9}\sigma_{max}^g$ for all light quark flavors because of the standard color factors. We now have to fix the projectile dependence of σ_{max}^i . At high energies, a pion-hadron cross section is about one half of the corresponding proton-hadron cross section. Since σ_{max}^i have the meaning of extreme values of hadron-hadron cross sections, we extend the above relation between pionic and nucleonic cross sections on σ_{max}^i as well. For definiteness, the projectile dependence will be represented by $\sigma_{max}^i(pions) = 0.4\sigma_{max}^i(protons)$. As a result, we have

only one free parameter, say $\sigma_{max}^g(protons)$, to describe the initial state effects. We will use

$$\sigma_{max}^g(protons) = 30mb. \quad (10)$$

The remaining parameters ($\sigma_{max}^q(protons)$ and $\sigma_{max}^{q,g}(pions)$) can now be calculated. The parametrization (9) and (10) will *not* be adjusted for different projectile energies or for different reactions.

For the quarkonium production, we have to take into account the final state interactions. In the study of the empirical regularities in the nuclear charmonium suppression [11], it was found that the x –independent part of nuclear suppression can be accounted for by $\sigma_f \approx 5.8$ mb. In our model, these value will simulate the x –independent final state interaction of produced heavy quarks. A self-consistent description of charmonium and dilepton production will prove *a posteriori* that in our model there is no room for a significant x_F –dependence of σ_f in the region $x_F \geq 0.2$. Final state effects have indeed a very modest x_F –dependence in some models (see, e.g., Ref.[6]). The fact that a quite large value of σ_f fits the final state interactions may indicate that heavy quark-antiquark pairs pass through the nucleus as non-singlet configurations, in agreement with the conjecture of Ref.[7]. In fact, σ_f is almost three times larger than the geometrical-size estimation for the J/ψ –proton total cross section[24]. A similar result for the final state $c\bar{c}$ –nucleon cross section has been obtained in some other models[6]. We think that the symmetrical description of initial and final state interactions in quarkonium production, adopted in Ref.[9], is not justified. There can be an important difference between the projectile hadron and the produced heavy quark configuration, which is not yet hadronized during its propagation in nuclear matter. As we will show, the price for the charm suppression fit of Ref.[9] is the underestimation by that model of initial state effects in the DY production by pions.

III. CHARMONIUM PRODUCTION

To calculate the charmonium production cross section, we take into account both the gluon-gluon fusion and quark-antiquark annihilation subprocesses. From the numerical results, we concluded that both channels are important in the considered x_F –region and the relative contribution of these two channels is in agreement with the result of Ref.[6]. The

proton-nucleus cross section is given by

$$\frac{d\sigma}{dQ^2 dx_F} = F_g^Q \frac{\sigma^{gg} x_1 x_2}{Q^2(x_1 + x_2)} g_1(x_1) g_2(x_2) + F_q^Q \frac{\sigma^{qq} x_1 x_2}{Q^2(x_1 + x_2)} \sum_{f=u,d} [q_1^f(x_1) \bar{q}_2^f(x_2) + \bar{q}_1^f(x_1) q_2^f(x_2)]. \quad (11)$$

The hard partonic cross sections σ^{ii} are taken from Ref.[25]. It is known that the nuclear structure functions, $g_2(x_2)$, $q_2(x_2)$ and $\bar{q}_2^f(x_2)$, are not equal to free nucleon structure functions. Nuclear structure functions measured in deep inelastic scattering have two pronounced peculiarities[15]: the shadowing at very small x_2 and the depletion (the EMC-effect) at $x_2 \geq 0.4$ (the antishadowing at $x_2 \sim 0.1$ is very small and will not be taken into account). The similar effects may be expected in the nuclear gluon distributions. In this section, we will not take into account these nuclear effects for the following reasons. If the nuclear shadowing at small x_2 is due to projectile initial state interactions in nuclear matter (in the case of electroproduction at small x_2 the projectile can be a virtual quark or meson[26]), then these effects are already included in factors F . We will argue that the alternative interpretation of nuclear shadowing, assuming the parton recombination in nuclei, is inconsistent with the charmonium production data. The EMC-effect is important at large x_2 , far from the region $x_2 \leq 0.14$ probed by the current experiments[1, 2]. The latter argument is not correct for the quarkonium production in the region $x_2 \sim 0.3$ studied in some recent experiments[17]. At such x_2 the EMC-effect in nuclear gluon and quark distributions can be noticeable. In this section we use the free proton structure functions from Ref.[27] for both $f_2(x)$ and $f_1(x)$.

The x_2 - and x_F -dependence of nuclear effectiveness α ($\alpha \equiv \ln(\sigma_A/\sigma_p)/\ln(A)$) for 800 and 200 GeV protons is shown in Figs.2 and 3. The agreement with the data at 800 GeV (the solid lines and the diamonds) is not surprising because we used this set of data to find the parametrization (9) and (10). The same for 200 GeV protons is shown by the short-dashed lines and crosses. This result is already non-trivial, especially the x_2 -dependence of α at 200 GeV. The net effect of final state interactions is represented by the solid and short-dashed lines in the small x_F -region in Fig.3.

The parton-recombination model prediction is shown by the dotted line in Fig.2. In this case, we have calculated α using the quark and gluon nuclear distributions from Ref.[6]

(the set 1 for gluons) and the constant value $\sigma_f = 5.8mb$ to approximately account for the final state effects. Note that the dotted line is expected to describe the data for both energies, within a kinematically allowed region of x_2 for each energy, because the difference between the results for two energies is less than 1% at the same x_2 . We can see from Fig.2 that the parton-recombination model is inconsistent with the data at both energies. Moreover, the parton-recombination model is ruled out by the data, if the origin of the nuclear suppression and its gross x_F -dependence are the same at both proton energies (this is very likely given the results presented in Fig.3). In fact, in the whole x_2 -region measured at 200 GeV, $0.037 < x_2 < 0.14$, the effect of the parton recombination is negligible. The same should be valid at 800 GeV in the region $0.01 < x_2 < 0.04$ since these two x_2 -regions correspond to the same x_F -region, taking into account the proton energy. . It follows from Fig.2 that the dotted line is in conflict with this expectation. Therefore the parton recombination model not only underestimates the charmonium suppression but also demonstrates a wrong x_2 -dependence of the suppression at different projectile energies. This can be corrected only if the parton recombination model will be combined with some other model of nuclear suppression, which predicts a specific dependence on the projectile energy at fixed x_F . For example, the EL-model does not have this property and cannot restore the correct x_2 -dependence, if being combined with the parton recombination model. We may assume that the nuclear parton recombination is less important than it is usually believed and will not take into account this effect in what follows.

Though our solid and short-dashed lines in Figs. 2 and 3 correctly reproduce the trend of the data, our results underestimate α at $x_2 > 0.06$. This discrepancy is eliminated if we assume that there is a 20%-enhancement of gluons in tungsten at $0.06 < x_2 < 0.15$. The calculated α with excess gluons included is shown by the long-dashed lines in Figs.2 and 3. The resulting χ^2 of our calculations is about 1 at both proton energies. Note that this excess gluon contribution affects α only at 200 GeV. The gluon enhancement we assumed is in qualitative agreement with the electroproduction data[28]. The momentum fraction carried by the excess gluons is about 3% for tungsten and is in qualitative agreement with the earlier estimations[29]. It may be assumed that the excess gluons play the role the excess

pions have been expected to play - they are responsible for the nuclear binding[29]. Observe that the distances involved by the excess gluons are of the order of internucleon distances in nuclei. It is also remarkable that the momentum fraction carried by excess gluons is comparable with the parton momentum fraction, lost because of the nuclear binding[30]. Is it an indication on the gluonic origin of nuclear forces? We will come back to this problem in Sec.V. Note that the excess gluons are not the only possible explanation of the above discrepancy. For example, a similar effect can be reproduced by an energy dependence of final state interactions.

The projectile dependence of the charmonium suppression is illustrated in Fig.4. The x_F -dependence of α for 200 GeV π^- -mesons without excess gluons (long-dashed line) is compared to the data for pions at this energy (diamonds). The same for protons at 200 GeV is shown by the short-dashed line and by crosses. It follows from this figure that our model correctly reproduces the projectile dependence of nuclear suppression. Remember that in our model, the projectile dependence is represented by the ratio $\sigma_{max}^i(pions)/\sigma_{abs}^i(protons)$, introduced in Sec.II. However, the long-dashed line still overestimates the suppression. The agreement with the data is improved when the excess gluon contribution is included (the solid line) in the same way as for proton-nucleus collisions.

To summarize, the absorption of initial partons can provide a self-consistent description of x_2 - and x_F -dependences of nuclear charm suppression at different energies and for different projectiles. In the region $0.06 < x_2 < 0.15$, the agreement with the data is improved by the inclusion of excess gluons.

IV. DY PRODUCTION BY PIONS

In the dilepton production by pions, the dominant contribution is due to quark-antiquark annihilation subprocess. Since projectile pions contain valence quarks and antiquarks, this reaction probes essentially the same target structure functions as the deep inelastic lepton scattering. In the case of exact strong factorization, the ratios R of nuclear to nucleon cross sections should coincide for these two reactions. Therefore the DY production by pions is an excellent test of strong factorization for nuclear targets. We now show that the weak factorization is more consistent with the data than the strong factorization. The cross section

for producing dilepton pairs in collisions of pions and nuclei is given by

$$\frac{d\sigma^{DY}}{dQ^2 dx_F} = F^{DY} \frac{\sigma^{qq} x_1 x_2}{Q^2 (x_1 + x_2)} \sum_{f=u,d,s} [q_1^f(x_1) \bar{q}_2^f(x_2) + \bar{q}_1^f(x_1) q_2^f(x_2)]. \quad (12)$$

The suppression factor F^{DY} , given by Eq.(7), was calculated as described in Sec.II. The data for this reaction[13] covers a large region of x_1 and x_2 for two pion energies, 140 and 286 GeV. Therefore we now have to take into account the nuclear modification of structure functions $q_2^f(x_2)$ and $\bar{q}_2^f(x_2)$. This modification will be represented by the depletion of nuclear structure functions at medium x_2 (the EMC-effect). The form of this depletion that we used in numerical calculations reproduces the electroproduction data for nuclear targets[15]. As it was discussed above, in the present model there is no physical reason to take into account the shadowing of nuclear structure functions at very small x_2 since such effects are assumed to be included in F^{DY} . We used the free nucleon structure functions from Ref.[27]. In numerical calculations, we integrated over the Q^2 - and x_F - regions, measured in the current experiment[13].

The x_2 -dependence of the ratio R for the tungsten at 140 and 286 GeV is shown in Figs. 5 and 6, respectively. Our results are represented by the solid lines, the predictions of the EL-model by the long-dashed lines and the strong factorization result (the EMC-ratio) by the short-dashed lines. Here and hereafter the EL-model predictions are calculated using Eq.(4) with $\kappa = 0.003$ and $n = 2$. The strong factorization is completely inconsistent with the data at 140 GeV ($\chi^2 = 5$). The EL-model ($\chi^2 = 2.3$ at 140 GeV) could explain the data with a larger parameter κ , but this would lead to a further violation of the limitation (3). Our results are in a reasonable accord with the data at 140 GeV ($\chi^2 = 1.1$).

The Fig.6 is less conclusive because the error bars in the most important region $x_2 \geq 0.3$ are larger than the difference between the theoretical predictions and $\chi^2 < 2$ for all models. By comparing Figs. 5 and 6, we conclude that in this reaction it is confusing to combine the data points for different energies because the x_2 -dependence of R for two energies is very different. For example in the region $0.1 < x_2 < 0.3$, the suppression at 140 GeV is much stronger than at 286 GeV. The "diffraction" minimum at $x_2 \approx 0.37$ in our predictions for $E_\pi = 286$ GeV takes place because the lower mesured mass region, $(4.2 GeV)^2 < Q^2 <$

$(8.5\text{GeV})^2$, is becoming kinematically forbidden at that x_2 . Observe that our model predicts a fast depletion at small x_2 because larger values of x_1 contribute in this region. New data at $x_2 \leq 0.1$ could help to test our model. As it will be shown in the next section, such depletion at small x_2 has been observed in the DY production by protons.

The x_1 –dependence of R is shown in Figs. 7 and 8. Taking into account the very large uncertainty in determining x_1 for the data points (not represented in these figures but shown in Ref.[13]), it is hard to make a preference between the models. A better statistics is needed to make a definite conclusion about the x_1 –dependence of R .

The dependence of R on the mass of the produced dilepton pair is shown in Figs. 9 and 10. The data at 140 GeV demonstrate a smooth behaviour and Fig.9 is quite conclusive: the present model ($\chi^2 = 0.5$) provides a much better agreement with the data than the EL-model ($\chi^2 = 2.6$) or the strong factorization ($\chi^2 = 4.5$). Note that the EL-model with $n=2$ could not fit the observed mass dependence of the suppression even with a larger κ . The point is that in the EL-model, the suppression decreases with produced mass because of the factor $(Q_0/Q)^n$ in (4) and this contradicts the trend of the data in Fig.9. The data at 286 GeV have large error bars in the most important region $(x_1 x_2)^{1/2} \geq 0.5$ and all theoretical curves have $\chi^2 < 1.5$ at this energy. However, it is our impression that our results are in a reasonable accord with the data at 286 GeV.

Let us summarize the results of this section. The Figs. 6,7,8 and 10 make no definite preference between the models. But the Figs. 5 and 9 allow us to conclude that the present model describes the DY production by pions much better than the EL-model. These two figures also present an evidence that the strong factorization is violated in nuclei.

V. DY PRODUCTION BY PROTONS

As in the case of the DY production by pions, the DY production by protons is dominated by the quark-antiquark annihilation subprocess. The difference between these two reactions is that protons probe mainly the antiquark content of a target, because protons have no valence antiquarks. Therefore this reaction is sensitive to a possible contribution of excess mesons in nuclei. The cross section for producing dilepton pairs in proton-nucleus collisions is given by Eq.(12). We have used the free nucleon structure functions as $q_2^f(x)$ and $\bar{q}_2^f(x)$

for the following reason. The nuclear modification of the antiquark distribution is unknown, but from the electroproduction data[15] it follows that the EMC-like nuclear effects should be unimportant in the region $x_2 < 0.3$, measured in the current experiment with 800 GeV protons [14]. The nuclear shadowing at small x_2 is not included in structure functions for the same reason as in the previous sections. Thus, in this reaction we will study the net effect of the initial state absorption represented by the factor F^{DY} . In the previous work[31], we have considered the same reaction with the constant parton absorption cross section. In that paper, we have concluded that the excess pion contribution with the average excess pion number per nucleon $n_\pi \approx 0.07$ is consistent with the data. We will now show that the x_1 -dependence of the absorption cross sections, introduced in the present paper, drastically changes the role of initial state absorption in this reaction and affects the conclusion of Ref.[31].

We used the free nucleon structure functions from Ref.[27]. We have integrated over the same mass region as in the experiment[14]. The x_2 -dependence of the ratio R for the iron and tungsten targets is shown in Fig.11 by the solid and dashed lines, respectively. An important result is that the suppression is concentrated mainly at $x_2 < 0.05$. The origin and the location of this depletion are exactly the same as in the case of the charmonium production by protons at 800 GeV (the solid line in Fig.2). This observation is supported by the fact that the calculated R from Fig.11 is in accord with the data ($\chi^2 = 0.7$). The A-dependence of the suppression at low x_2 is also well reproduced by our model. In this situation, there is no room for any noticeable contribution of excess pions, at least at $x_2 \geq 0.04$. If our present model is correct, than the upper limit for the momentum fraction carried by excess pions is about 1%. This conclusion is qualitatively consistent with the results of Ref.[32] that the structure functions of off-mass-shell pions are significantly depleted. In this case the excess gluons, considered in Sec.III, are another possible candidate to carry the missing parton momentum in nuclei[30].

The x_F -dependence of R for the iron is shown in Fig.12. Though the qualitative trend of the data is more or less reproduced by the theoretical curve, the suppression at $x_F > 0.5$ is overestimated by our model. In that region, the values $x_2 \leq 0.04$ have the noticeable

contribution. We may assume that in the region $x_2 \leq 0.04$, not covered by the data points in Fig.11, either the nuclear structure functions are enhanced due to some excess particles or our model overestimates the suppression. In any case, our model leaves no room for the parton recombination effects in this reaction, as well as in the charmonium production.

VI. DISCUSSION

We have assumed a new type of initial state effects, the x_1 -dependent absorption of fast initial partons. As we argued in Sec.I and in Ref.[10], such effects in nuclei are not *a priori* excluded by the factorization theorem forecasts. Using only one physically motivated empirical function for the absorption cross sections, we have qualitatively explained nuclear effects in several reactions with fast protons and pions. We claim that in the currently discussed experiments on charmonium production, the x -dependence of nuclear suppression can be accounted for by the initial state interaction we assumed. In this case, the final state effects in the region $x_F > 0$ can be fitted by the constant cross section σ_f . With the excess gluon contribution included, the present model can explain also the energy and projectile dependence of the charmonium suppression. The dilepton production suppression is also qualitatively explained, though our model sometimes overestimates the suppression. This possible discrepancy can be removed by adjusting the parameters, for example by reducing $\sigma_{max}^q/\sigma_{max}^g$. The present results are obtained using a minimum of arbitrary assumptions and allow us to conclude that this model is able to self-consistently describe nuclear effects in different hadroproduction reactions. The Υ - and J/ψ -production at low and negative x_F - demands the incorporation of comover interaction and nuclear modification of gluon distribution and will be considered somewhere else.

If the present model is correct, then the following qualitative conclusions can be made.

- 1) The strong factorization is violated by the initial state interactions in hadroproduction on nuclei. The weak factorization takes place instead.
- 2) The parton recombination has no significant contribution to charmonium suppression.
- 3) There is an indication of the presence of excess gluons in nuclei at $0.06 < x_2 < 0.15$, carrying about 3% of the total momentum.
- 4) The energy-loss model cannot self-consistently describe the quarkonium and dilepton production if the mass dependence of the energy loss is given by $1/Q^2$.
- 5) There is no

indication of the excess pion contribution in dilepton production in proton-nucleus collisions. The fraction of the nuclear momentum, lost by partons due to nuclear binding, can be carried by the excess gluons. This point illustrates the difference between the binding correction[30] and pionic models[33] for the EMC-effect: the former is not based on the presence of excess pions in nuclei.

The above conclusions do not mean that the soft initial state interactions, assumed by the EL-model, take no place in nuclei. Instead, these interactions may be responsible for the observed p_T -dependence of hadroproduction on nuclei. But the role of these interactions in the x -dependence of nuclear suppression can be minor, in agreement with the limitation (3). The validity of the present model can be tested, e.g., by remeasuring with a better accuracy the DY production by pions, where we predict several specific peculiarities. We believe that the results of this paper can be useful for an analysis of nuclear effects in hadro- and electroproduction, even if our present model will be ruled out by future studies.

ACKNOWLEDGMENTS

I would like to thank the Research Institute for Particle and Nuclear Physics, Budapest, for the warm hospitality.

This work was funded by the Russian Foundation of Fundamental Research (contract No 93-02-14381).

References

- [1] J.Badier *et al.*, Z. Phys. C **20**, 101 (1983).
- [2] D.M.Alde *et al.*, Phys. Rev. Lett. **66**, 133 (1991).
- [3] S.J.Brodsky and P.Hoyer, Phys. Rev. Lett. **63**, 1566 (1989).
- [4] R.Vogt, S.J.Brodsky and P.Hoyer, Nucl.Phys. B **360**, 67 (1991).
- [5] F.E.Close, J.Qiu and R.G.Roberts, Phys. Rev. D **40**, 2820 (1989).
- [6] C.J.Benesh, J.Qiu and J.P.Vary, Phys.Rev. C **50**, 1015 (1994).
- [7] G.Piller, J.Mutzbauer and W.Weise, Z. Phys. A **343**, 247 (1992).
- [8] J.Hüfner, Y.Kurihara and H.J.Pirner, Phys. Lett. B **215**, 218 (1988).
- [9] S.Gavin and J.Milana, Phys. Rev. Lett. **68**, 1834 (1992).
- [10] S.V.Akulichev, Z. Phys. A **349**, 185 (1994).
- [11] C.Gerschel, J.Hüfner and E.Quack, Preprint GSI-95-14, Darmstadt, Germany (1995).
- [12] T.Matsui and H.Satz, Phys. Lett. B **178**, 416 (1986).
- [13] P.Bordalo *et al.*, Phys. Lett. B **193**, 368 (1987).
- [14] D.M.Alde *et al.*, Phys. Rev. Lett. **64**, 2479 (1990).
- [15] M.Arneodo, Phys. Rep. **240**, 301 (1994).
- [16] M.S.Kowitt *et al.*, Phys. Rev. Lett. **72**, 1318 (1994);
(E653 Collaboration) K.Kodama *et al.*, Fermilab Preprint CMU -HEP93-15 (1993).
- [17] D.M.Alde *et al.*, Phys. Rev. Lett. **66**, 2285 (1991);
M.J.Leitch *et al.*, Nucl. Phys. A **544**, 197c (1992).
- [18] J.C.Collins, D.E.Soper and G.Sterman, Nucl. Phys. B **261**, 104 (1985).

- [19] G.T.Bodwin, Phys. Rev. D **31**, 2616 (1985).
- [20] A.H.Mueller, in *Proceedings of the XVII Rencontre de Moriond* (1982).
- [21] G.T.Bodwin, S.J.Brodsky and G.P.Lepage, Phys. Rev. Lett. **47**, 1799 (1981).
- [22] S.J.Brodsky and P.Hoyer, Phys. Lett. B **298**, 165 (1993).
- [23] M.Hofmann *et al.*, Nucl. Phys. A **566**, 15c (1994).
- [24] B.Povh and J.Hüfner, Phys. Rev. Lett. **58**, 1612 (1987).
- [25] H.Fritzsch, Phys. Lett. B **67**, 217 (1977).
- [26] S.J.Brodsky and H.J.Lu, Phys. Rev. Lett. **64**, 1342 (1990);
S.A.Kulagin, G.Piller and W.Weise, Phys. Rev. C **50**, 1154 (1994).
- [27] E.Eichten *et al.*, Rev. Mod. Phys. **56**, 569 (1984).
- [28] P.Amaudruz *et al*, Nucl. Phys. B **371**, 553 (1992).
- [29] L.L.Frankfurt, M.I.Strikman and S.Liuti, Phys. Rev. Lett. **65**, 1725 (1990).
- [30] S.V.Akulichev, S.A.Kulagin and G.M.Vagradov, Phys. Lett. B **158**, 485 (1985);
S.V.Akulichev, S.Shlomo, S.A.Kulagin and G.M.Vagradov, Phys. Rev. Lett. **55**, 2239
(1985).
- [31] S.V.Akulichev, Preprint INR-0878-95, Moscow (1995)(unpublished).
- [32] C.M.Shakin and W.-D.Sun, Phys. Rev. C **50**, 2553 (1994).
- [33] M.Ericson and A.W.Thomas, Phys. Lett. B **132**, 112 (1983).

Figure captions.

FIG.1. The function $\sin^6(x\pi/2)$, representing the x -dependence of parton-nucleon absorption cross sections.

FIG.2. The nuclear effectiveness α versus x_2 for charmonium production in proton-nucleus collisions at the energies 800 GeV (solid line) and 200 GeV (short-dashed line). The latter with excess gluons included is represented by the long-dashed line. The parton-recombination model prediction is shown by the dotted line. The data at 800 GeV (diamonds) and 200 GeV (crosses) are from Refs. [2] and [1], respectively.

FIG.3. The same as in Fig.2 versus x_F (without the parton-recombination model prediction).

FIG.4. α versus x_F for the charmonium production in negative pion-nucleus collisions at 200 GeV (long-dashed line). The same with excess gluons is shown by the solid line. α for 200 GeV protons without excess gluons is shown by the short-dashed line. The data (diamonds for pions and crosses for protons) at 200 GeV are from Ref.[1]

FIG.5. Ratio of the dilepton yield for tungsten to proton versus x_2 in pion-nucleus collisions at 140 GeV: the solid line is the present model result, the long-dashed line is the result of the energy-loss model [9] and the short-dashed line is the strong factorization result. The data are from Ref.[13].

FIG.6. The same as in Fig.5 at 286 GeV.

FIG.7. The same as in Fig.5 versus x_1 .

FIG.8. The same as in Fig.5 versus x_1 at 286 GeV.

FIG.9. The same as in Fig.5 as a function of dimensionless dilepton mass.

FIG.10. The same as in Fig.5 as a function of dimensionless dilepton mass at 286 GeV.

FIG.11. Ratio of the dilepton yields for protons at 800 GeV for iron (solid line) and tungsten (dashed line) as a function of x_2 . The data for iron (diamonds) and tungsten (crosses) are from Ref.[14].

FIG.12. Ratio of the dilepton yields for protons at 800 GeV for iron versus x_F . The data are from Ref.[14].























